Hongwei Li*,
Hairong Zhu,
Ning Dai.
Xinli Yan

J. Electrical Systems 14-2 (2018): 77-87

Regular paper

Multi-energy Coordinated Optimization for both Supply and Demand Sides of Energy Internet System

JES Journal of Electrical Systems

Abstract: The energy Internet based industrial revolution will become the key technical means to promote the transformation and development of China s energy industry. To solve the problem of the randomness of supply and demand in current power system, the theory of synergetic controllability of both supply and demand sides was put forward in this paper. The synergetic optimization model has been established based on the complementary supply network of the electricity and the thermal energy by taking the environmental cost of investment and operation as the optimal objective. The teaching-learning based optimization algorithm (TLBO) was used to solve this multi-objective nonlinear programming model. The test system proves that the proposed model can realize the bilateral collaborative optimization of supply and demand. It shows strong performance and proposes a new idea to solve these energy Internet problems.

Keywords: energy Internet (EI); supply and demand; coordinated optimization; teaching-learning based optimization algorithm.

Article history: Received 17 October 2017, Accepted 17 March 2018

1. Introduction

In recent years, with the rapid development of new energy and information network technology, a new energy development system, namely energy Internet (**EI**), has been generally recognized. It provides a reasonable and feasible way to solve the problem between energy and environment. Power system is the core of **EI**, and distributed renewable energy is the key energy source for **EI**. **EI** is a complex multi-network flow system which tightly coupled with other systems such as natural gas networks and transportation networks. Because of its multi-energy complementarity, complex energy supply modes and changes from demand load fluctuations, **EI** system needs to manage the dispatch and operation of the micro-grid based on the user side. The traditional optimization method is difficult to control **EI** system and cannot guarantee the economy and efficiency of the operation scheme [1-7]. Therefore, it is urgent and necessary to solve the problem and to propose a better optimization system model for the multi-energy complementary network from both supply and demand sides.

At present, in order to solve the energy shortage and environmental pollution problems, some achievements have been achieved in the operation control of the **EI** system, such as all kinds of control algorithm and prediction models. In [8-9], the significance of **EI** was described from the value perspective and the key technology of city energy Internet has been put forward. It stresses that the access proportion of renewable generations can be improved sharply based on the comprehensive demand side response mode. In [10-11], it puts forward a horizontal multi-energy complementary pipeline model including electricity, gas, heat, etc. Moreover, the coordination control strategy has been studied from the vertical aspect along source, network, load and storage. In [12], a thermo-electric energy supply network planning model was presented in a regional energy supply system. Based

* Corresponding author: Hongwei Li, email: lhw@swpu.edu.cn
School of Electrical Information Engineering, Southwest Petroleum University, Chengdu 610500, China.

on this model, the total cost can be reduced by considering the coupling and replacement relations between the thermal and electrical loads.In [13], it introduces the load forecasting model in energy management system from the user side of **EI** system, and then it discusses the interaction mechanisms between the operators' participation and market competition, and between the operators and the local resources. In [14-15], it adopted the comprehensive evaluation method and difference method to evaluate the economic and social benefits of the DCCHP (distributed combined cooling heating and power, DCCHP) system in micro-grid. The block chain technology is similar to **EI** concept, so in [16], it states the function of block chain technology used in different parts of **EI**, such as measurement authentication, market transaction and cooperative organization etc. In [17], it focuses on the collaborative planning of combined heat and power (CHP) in summer and winter. An improved hybrid algorithm based on PSO (particle swarm optimizer) and ant colony was used to solve this mixed integer nonlinear programming problem.

In summary, the current research results mainly aim at evaluating the system architecture, functional system, and economic benefits of **EI** from only supply side or only demand side. There are less researches on the coordination optimization among cold, heat, electricity and gas at the system level. In view of the above problems, this paper studied the basic framework of **EI** system from both supply and demand sides. By taking heat, electricity and gas as the breakthrough points, the minimum comprehensive cost of investment, operation and environment is selected as the objective function. The scheduling optimization model has been established based on electricity, heat and gas multi-energy supply network at time scale. Teaching-learning based optimization (TLBO) was adopted to solve the optimal solution of the model. The results show that it not only meets the needs of the users, but also effectively reduces the comprehensive cost of the system and the environment. Then the safety and stability of the system operation can be improved and the expected effect can be achieved.

2. Energy Internet system network

2.1 Energy Internet system architecture

The **EI** system usually consists of four complex network systems, that is, power system, heating system, natural gas network and information network. The power system is the core of **EI** and serves as the hub for the transformation of other energy sources. Moreover, with the emergence and deepening of the shale gas revolution, the cost of producing natural gas will continue to decrease, so the operation of the natural gas network will affect the economic efficiency and reliability of the power system. In addition, **EI** is compatible with secondary energy networks, such as heating networks. Some of them may be the important byproducts of distributed gas-fired power generation. As a result, the integration of the power network and the heating network can be realized by using combined cooling, heating and power system as the link. Finally, various energy networks within the above system (including distributed power supplies, energy storages, load demands and so on) need to be planned through a powerful information network.

For example, one block diagram of **EI** network is shown in Fig. 1. With the help of an intelligent energy manager to records the historical data of supply and demand sides and to make scheduling strategy with the optimization algorithms, the energy conversion control can be realized to meet the user's energy requirements according to the real-time operation information. In this paper, a multi-energy coordinated optimization model is built to achieve the overall coordination between the supply and demand sides of the multi-energy system.

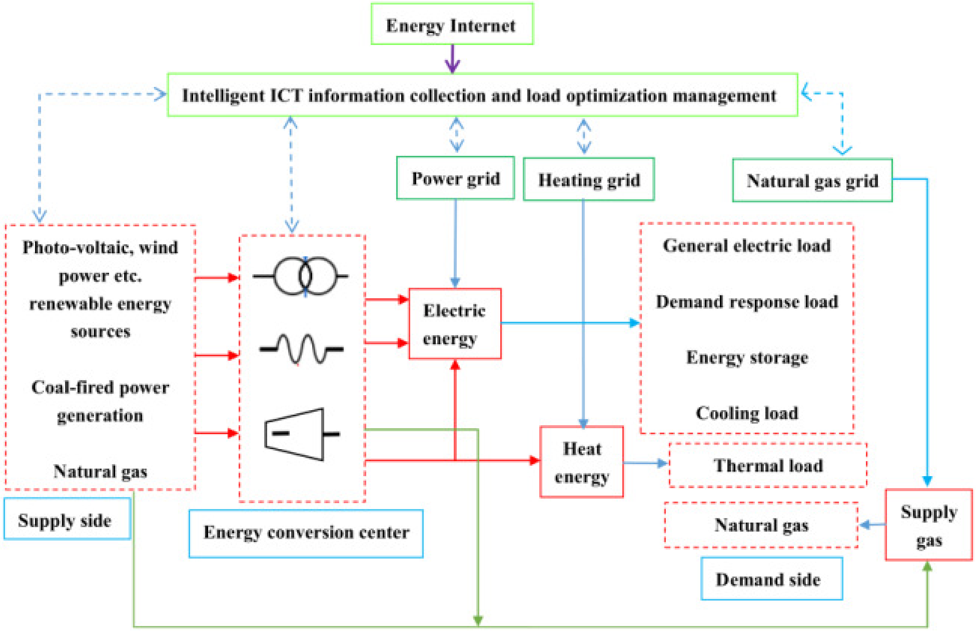

Fig. 1 block diagram of EI system

1.2 Energy Internet operation model

In 2008, German Federal Ministry of Economy and Technology and the Ministry of Environment jointly launched a technological innovation program (E-Energy), which aims to build a future energy system based on ICT (Information Communications Technology). With the further study, E-Energy put forward the concept of German energy Internet system from the point of the compatibility between ICTs and whole power system. At present, some technologies in E-Energy can provide experience to construct **EI** for other countries[18], which is mainly reflected in the following three aspects:

(1) The intelligent ICT is used to realize the optimization management of the loads. It can go deep into the user's domestic appliance level. As a result, whether it is ordinary small electrical load, or cold and hot load with large power consumption, etc, the switch-on or switch-off can be selected freely.

(2) The advanced electronic measurement instruments will obtain big data of power system from users and provide the necessary information to E-Energy system. Then, E-Energy system can analyze the power usage characteristic of different users based on the big data.

(3) The system will also collect and forecast other data information which can affect the energy supplies in the region, like light intensity, wind speed, etc. Those data combined with the user's data and generation data, etc. are sent to transporters of system operators, ICT gateways of the users and the energy providers, and then the optimal generation plan and power consumption plan can be obtained to realize the coordination and optimization between power supply and demand.

2 Coordinated optimization model for energy Internet

Under the current conditions, multi-energy coordinated optimization model for **EI** system and its implementation still need to face many problems. So in this paper, an aggregate and complementary supply system of electricity, heat and natural gas is proposed which reflects the "substitutability" of different energy sources. For example, when gas turbines generate electricity, there will be part of the thermal energy as an important by-product to form CHP system.

2.1 objective function

The optimal scheduling model aims to achieve two objectives: to minimize the investment operation cost and environmental cost, as follows:

$$\begin{aligned} \min F_1 &= \min[\sum_i C_{pv}^i G_{pv}^i + \sum_j C_{wind}^j G_{wind}^j + \sum_n C_{gas}^n G_{gas}^n + \sum_m (C_G^m + C_G^{m.on}) G_G^m] \\ \min F_2 &= \min[\sum_m G_G^m (f_d + f_{co_2} + f_{so_2} + f_{No_x})] \end{aligned} \tag{1}$$

Where, C_{pv}^i and G_{pv}^i are generating cost and generating capacity of photo-voltaic respectively. C_{wind}^j and G_{wind}^j are generating cost and generating capacity of wind power respectively. C_{gas}^n and G_{gas}^n are generating cost and generating capacity of gas respectively. C_G^m 、 $C_G^{m.on}$ and G_G^m are electricity purchasing cost, operating cost and electricity consumption from main grid respectively. f_d , f_{co_2} , f_{so_2} and f_{No_x} are unit environmental costs as for soot, CO_2 , SO_2 , NO_x emissions respectively.

2.2 constraint condition

1) power balance constraint

$$\begin{aligned} G_{T(t)} &= G_{S(t)} + G_{B(t)} + G_{Z(t)} + G_{L(t)} \\ G_{S(t)} &= G_{pv(t)} + G_{wind(t)} = \int_{i=1}^{t} P_{pv(i)} + \int_{i=1}^{t} P_{wind(i)} \\ G_{Z(t)} &= G_{gas(t)} = \int_{i=1}^{t} P_{gas(i)} \end{aligned} \tag{2}$$

Where, $G_{T(t)}$, $G_{S(t)}$, $G_{B(t)}$, $G_{Z(t)}$ and $G_{L(t)}$ are the total electricity supply, the electricity from the distributed generations, the electricity from the grid, the electricity of the gas unit and the total loss of the system respectively within the *t* period. $P_{pv(i)}$, $P_{wind(i)}$ and $P_{gas(i)}$ are the generating powers of the solar energy units, the wind turbine and the gas turbine units at the *i* moment respectively.

2)demand response constraint

Demand response is the key technology and realizing way of **EI**. It is the important manifestation of the users to participate in **EI**. Demand response relies on the energy intelligent management device at the user side to realize the coordination and optimization of supply and demand in **EI**.

Capacity constraint for load change,

$$\begin{aligned} R_{j(\Delta t)}^T &= X_{j(\Delta t)}^T * \Delta R_j^T \\ \sum_{j=1}^{N} R_{j(\Delta t)}^T &\le R_{j.\max(\Delta t)}^o = P_{j(\Delta t)}^{BC} \end{aligned} \tag{3}$$

Balance constraint of the transferable loads

$$\begin{aligned} &\sum_{j=1}^{N} P_{j(\Delta t)}^{BC} = \sum_{j=1}^{N} P_{j(\Delta t)}^{DC} \le P_{\max(\Delta t)}^{BC} \\ &P_{(\Delta t)}^{DC} = \sum_{j=1}^{N} P_{j(\Delta t)}^{DC} + P_{(\Delta t)}^{Fix} + P_{(\Delta t)}^{Rand} \end{aligned} \tag{4}$$

Where, $R_{j(\Delta t)}^{T}$ is the transferred load amount in Δt. ΔR_{j}^{T} is the transferred amount for the type j load. $X_{j(\Delta t)}^{T}$ is the unit number. P_{j}^{BC} and P_{j}^{DC} are loads before and after transferring respectively. $P_{(\Delta t)}^{Fix}$ and $P_{(\Delta t)}^{Rand}$ are the fixed load and random load respectively.

3) generating power constraint

$$\begin{aligned} &Q_{G}^{\min} \le Q_{G}^{m} \le Q_{G}^{\max} \qquad -\rho_{G,d}\Delta t \le \Delta Q_{G,t} \le \rho_{G,u}\Delta t \\ &Q_{gas}^{\min} \le Q_{gas}^{n} \le Q_{gas}^{\max} \qquad -\rho_{gas,d}\Delta t \le \Delta Q_{gas,t} \le \rho_{gas,u}\Delta t \\ &Q_{pv}^{\min} \le Q_{pv}^{i} \le Q_{pv}^{\max} \qquad Q_{pv(t)} = \min[Q_{c}, \theta_{(t)} S_{pv} \eta_{pv}] \\ &Q_{wind}^{\min} \le Q_{wind}^{j} \le Q_{wind}^{\max} \\ &Q_{wind} = \begin{cases} 0 & 0 \le sv_{t} \le v_{on}, sv_{t} \ge v_{cut} \\ A + B \times sv_{t} + C \times sv_{t}^{2} & v_{on} \le sv_{t} \le v_{N} \\ P_{N} & v_{N} \le sv_{t} \le v_{cut} \end{cases} \end{aligned} \tag{5}$$

Where, $\Delta Q_{G,t}$ and $\Delta Q_{gas,t}$ are change quantities of main grid and gas turbine, $\rho_{G,d}$ and $\rho_{G,u}$ are the maximum descending and rising rates of main grid per unit time. $\rho_{gas,d}$ and $\rho_{gas,u}$ are the maximum descending and rising rates of the gas turbine per unit time. $Q_{pv(t)}$ is the generating power of solar power units at the t moment; Q_{c} is the rated installed capacity of solar power; $\theta_{(t)}$ is the local solar radiation quantity; S_{pv} is the solar panel area; η_{pv} is the generating efficiency of solar power units; $Q_{wind(t)}$ is the generating power of wind turbines at t moment.

Here,

$$\begin{aligned} A &= \frac{1}{(v_{on}-v_{N})^{2}}\left[v_{on}(v_{on}+v_{N}) - 4(v_{on}+v_{N})\left(\frac{v_{on}+v_{N}}{2v_{N}}\right)^{3} \right] \\ B &= \frac{1}{(v_{on}-v_{N})^{2}}\left[4(v_{on}+v_{N})\left(\frac{v_{on}+v_{N}}{2v_{N}}\right)^{3} - 3(v_{on}+v_{N}) \right] \\ C &= \frac{1}{(v_{on}-v_{N})^{2}}\left[2 - 4\left(\frac{v_{on}+v_{N}}{2v_{N}}\right)^{3} \right] \end{aligned} \tag{6}$$

Where, v_{on}, v_{N}, v_{cut} and P_{N} are the start-up wind speed, rated wind speed, cut-off wind speed and rated power of wind turbine respectively.

4) thermoelectric coupling constraint

$$\sum_{j=1}^{m} Q_{j} / \sum_{i=1}^{n} P_{i} \ge \tau \tag{7}$$

Where, Q_{j} is the output of heat supply unit j, P_{j} is the output of power supply unit i, τ is the annual thermoelectric ratio of CHP, usually is 50%.

Here, it should be emphasized that the photo-voltaic and wind power outputs have strong randomness. So in order to ensure the overall system reliable operation, the system need to introduce a large number of flexible and controllable generators into the system to realize the complementary and coordinated control among different energy flows, in which energy flows also includes the controllable demands at users' sides.

5) storage device constraints

$$
\begin{aligned}
&R_{\min}^{i} \le r_{k}^{i} \le R_{\max}^{i} \\
&soc_{\min} \le soc_{t} \le soc_{\max} \\
&r_{kt}^{i} \cdot t \le \Delta soc \cdot S_{\max}
\end{aligned}
\tag{8}
$$

Where, r_{kt}^{i} are the charging and discharging power of storage device i within the t period; $R_{\min}^{i}$ and $R_{\max}^{i}$ are the minimum and maximum power of storage device i. soc_t and Δsoc_t are the power and power variation of storage devices within the t period.

6) user load curtailment constraint

$$D_{\min} \le d_k \le D_{\max} \tag{9}$$

Where, $D_{\min}$ and $D_{\max}$ is the allowable minimum and maximum curtailment loads within the t period.

3 Improved TLBO algorithm

3.1 original TLBO algorithm

The TLBO algorithm is a teaching-learning process inspired algorithm proposed by Rao based on the effect of the teacher influence on the output of learners in a class. The algorithm describes two basic learning modes of the learners: (i) learning through teacher (known as teacher phase) and (ii) interacting with the other learners (known as learner phase).

Teacher is usually considered as knowledgeable people in the society, who serve for cultivating future excellent talents and share knowledge with the learners. So the best solution (the best individual of the population) acts as a teacher in the teacher phase. Every learner acquires knowledge from the teacher, and then the level of knowledge of the class increases.

At any iteration *i*, assume that there are '*m*' number of subjects (i.e., design variables), '*N*' number of learners(i.e., population size, k = 1, 2,…, *N*). The operation of teaching can be described as follows.

$$
\begin{gathered}
x_{mean} = \frac{1}{N}\sum_{i=1}^{i=N} x_i \\
TF_i = round(1 + rand(0,1)) \\
x_i^{new} = x_i^{old} + rand_i \times (x_{teacher} - TF_i \times x_{mean})
\end{gathered}
\tag{10}
$$

Here $rand(0,1)$ and $rand_i$ are the uniform random numbers between 0 and 1, respectively, TF_i is a teaching factor that decides the value of the mean value to be changed; round(x) represents x is rounded to the nearest integer, x_i^{new} and x_i^{old} denote the ith learner's mark before or after learning from the teacher, respectively; $x_{teacher}$ is the best individual of the whole population, which represents the teacher in the teacher phase.

After every learner finishes the process of teaching, he interacts randomly with other learners through communications, consultations and discussions etc. A learner learns from a good student who has more knowledge. The learning process is expressed as below.

$$
x_i^{new} = \begin{cases} x_i + rand_i \times (x_i - x_r) & if\left(f(x_i) < f(x_r)\right) \\ x_i + rand_i \times (x_r - x_i) & else \end{cases}
\tag{11}
$$

where x_r is randomly selected from the whole population.

The flow chart of the original TLBO algorithm is shown in Fig. 2.

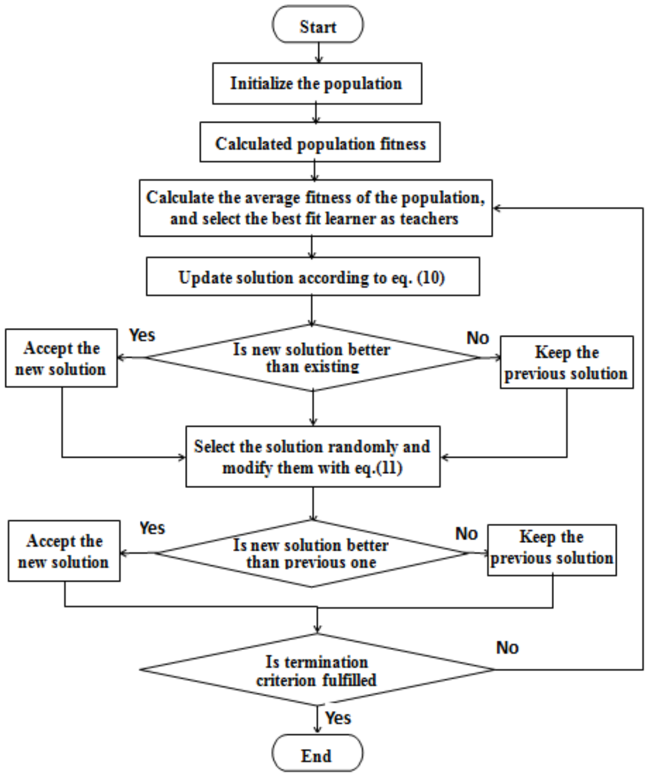

Fig. 2 flow chart of original TLBO algorithm

3.2 Improved TLBO algorithm (ITLBO)

TLBO algorithm has many advantages, but its shortcomings are obvious, that is, when dealing with complex optimization problems, it is prone to premature and trapped into the local optimal solution. To overcome this shortcoming, a self-driven learning approach or self-learning ability is added into TLBO algorithm. By introducing a SR (Self-Learning Rate) factor, an improved teaching-learning based optimization (ITLBO) algorithm is obtained, which can improve the TLBO algorithm's search ability. The steps of ITLBO algorithm are described as follows:

Step1: Initialize the number of students (population), subjects (design variables) and termination criterion.

Step2: Teaching phase. Modify solution based on best solution (teacher) with (10) and update the solution after the teaching phase: if $f(X_i^{new}) < f(x_i^{old})$,then X_i^{new} replace x_i^{old} .

Step3: Then the self-learning is carried out in the teaching phase, its expression is:

$$x_i^{new} = \begin{cases} x_i^{old} + rand(0,1)\times(x_i^U - x_i^L), if \quad rand_i < SR \\ x_i^{old}, \qquad otherwise \end{cases} \tag{12}$$

where, x_i^U and x_i^L are upper and lower limits for each design variable. SR refers to the self-learning rate which is predetermined. With repeated experiments, it is appropriate when SR is between 0.6 and 0.9.

Step4 : Learning phase. It is the same as described in Fig.2.

Step5: If termination criterion is met, the iteration ends; otherwise, go to step 3.

4 Test results and analyses

Taking an ecological park demonstration project in China for test system. The project takes electricity as the energy center and includes many other kinds of energy, such as cold, heat and gas energy. The required basic data are listed in Table 1. This paper takes advantage of a simple user side micro-grid system to test the proposed model and the optimization method under **EI** environment. The test system is connected to a wind turbine, a solar photo-voltaic power station and a gas turbine unit.The maximum output of the gas turbine unit is 100kW and the conversion efficiency is set as 80%. Typical outputs of wind turbine and solar photo-voltaic station in 24 hours period are shown in Fig. 3.

According to the types and characteristics of different energy sources, the parameters in ITLBO algorithm include the size of the population, 20, the maximum iteration number, 80, the dimension of the problem, 5, and the SR is 0.8. In addition, the DE algorithm requires additional specific parameters, such as the scaling factor(F) and the cross rate (CR).

Table 1. system construction and operation cost

Project	Cost/kw.h	Project	Cost/kw.h
PV equipment	19000	CO_2 emission	0.01
PV operation	0.01	SO_2 emission	0.04
WT equipment	17000	NO_x emission	0.06
WT operation	0.04	Dust emission	0.01
Gas turbine unit	8100	Coal-fired power	0.75

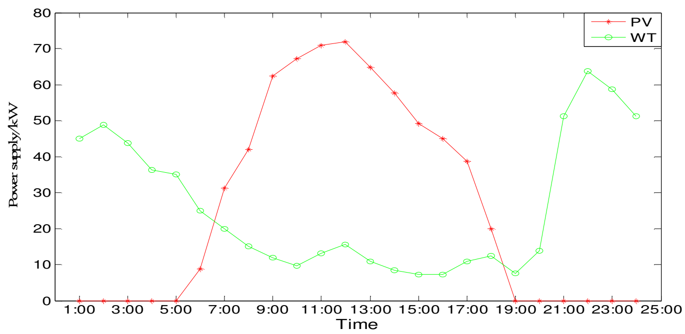

Fig. 3 24-hour typical output profiles for PV and WT

The typical daily load trasfer profile for the test system are shown in Table 2. Accoring to the actual needs, the transfer load of each type is not more than 25kW at one time. At the same time, the goal is to maximize the utlization of renewable energy and clean energies based on collaborative management between demand response and storages. Based on the time scale characteristics of distributed power and transferable load, the ITLBO algorithm is used to get reasonable dispatch of transferable load, which is an important way to implement bilateral coordination of **EI** system. The economy and environmental benefits of **EI** system are realized and the coordinated operation strategies of multiple energy system are shown in Fig. 4.

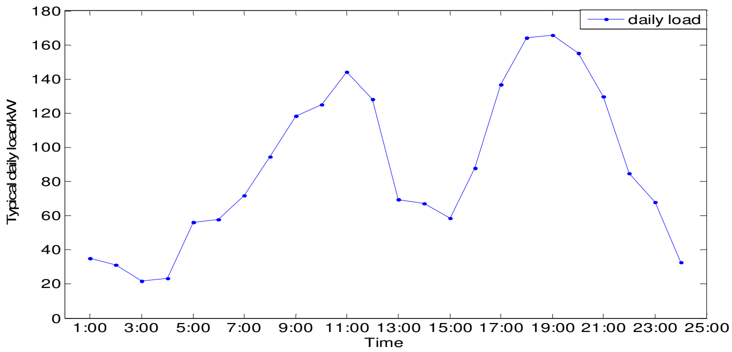

Fig 4. typical daily load curve

At present, energy storages have the advantages of fast response, high flexibility and good controllability.Therefore, energy storages can be charged when the total power from the energy sources is larger than the electric loads, otherwise, it will discharge to supply the loads. By coordination, it can reduce electricity purchase from the main power grid and realize the full usage of new energies. Based the data of Table 1 and Figs.3&4, the problem has been solve with the ITLBO algorithm. The results are shown in Fig.5 and table 2.

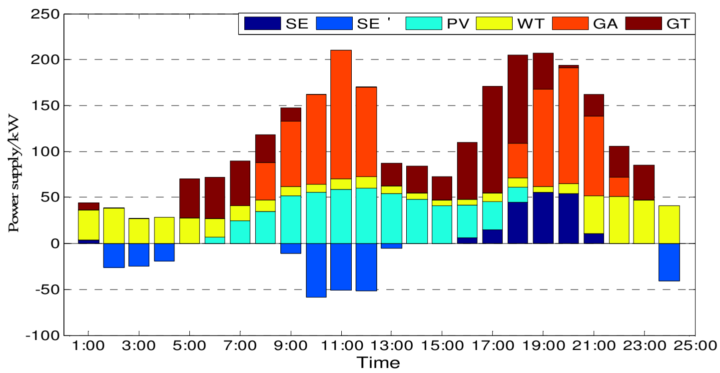

Fig. 5 the optimization results of test system

The power is supplied by energy storage (SE), distributed wind power (WT), main grid purchase (GT), gas power generation (GA) and distributed photo-voltaic (PV). The available photo-voltaic and wind power resources are abundant in this area and when the load demand is low at night, part of the wind generated power has been stored into the energy storage devices. At 6:00-14:00, light condition is better and the wind speed is strong, so the storage devices will continue to be on charge. At 18:00-21:00, the load demand gradually rises to the peak hour, so the energy released by the storage devices can relieve the peak hour demand. At 22:00-0:00, power consumption decreases gradually to the valley time, the wind power is consumed first and if insufficient, it needs energy from gas turbine generation and main grid purchasing. At 0:00-6:00, the energy price of power grid is lower, so load demand mainly depends on the main grid and wind power supply.

In addition, the economic benefits of multi-energy coordination between supply and demand of the **EI** are compared and the results are listed in Table.3. It can be seen, the total cost of the system is 914 thousand yuan based on the original mode, and the total cost of the system is 572 thousand yuan by the optimization model based on ITLBO algorithm. The improved rate is 37.4% and the reduction rate of environmental cost reaches 28.8%. It proved that through the coordinated control of gas turbine unit, wind power unit and photo-voltaic generation unit, it can effectively reduce the system operating cost and environmental comprehensive cost.

In order to verify the performance of ITLBO algorithm, the ITLBO algorithm, TLBO algorithm and DE algorithm are tested and compared based on the same system. The results are shown in Table.2. The iteration result diagrams are shown in Fig.5 for those three different methods.

Table 2. the optimal results with different methods

Project	Generation cost	Operation cost	Control cost	Energy storage cost	Environ-mental cost	Total cost
Previous	570000	94000	0	0	250000	914000
DE	350000	15000	28000	6000	183000	582000
TLBO	350000	14000	25000	6000	179000	574000
ITLBO	350000	14000	24000	6000	178000	572000

Because the traditional DE algorithm requires more setting parameters, it has a relatively poor and slow convergence. TLBO has the ability of fast searching, so it can be seen from Table 3 that TLBO and ITLBO algorithms obtained the better results. Moreover, the iterative number of the ITLBO algorithm is 6 times, which is better than the iterative numbers of the TLBO algorithm, 11 times. That is, ITLBO algorithm has better optimization ability and fast calculation speed, so the optimization results of ITLBO are better than those from the TLBO and DE algorithms.

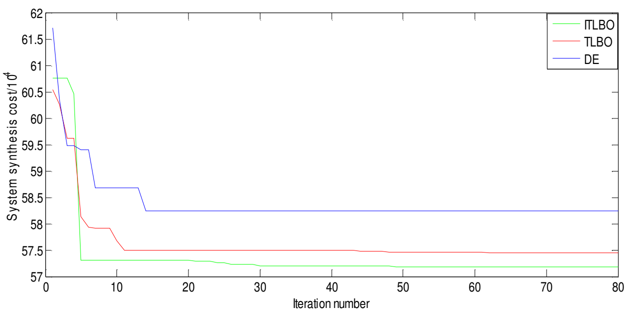

Fig.5 the iteration results for different methods

5. Conclusion

In this paper, the comprehensive coordinated optimization model was constructed considering the electricity, heat, gas energy supply network and the load response of demand sides. The ITLBO algorithm is used to solve the optimization problem. The TLBO algorithm has the advantages of few parameters, easy programming and fast convergence. ITLBO algorithm has much stronger global search ability and can get much better results. The results of test system show that with the coordinated control of gas turbine unit, wind power unit and photo-voltaic generation unit, it can effectively reduce the system operating cost and environmental comprehensive cost.

Acknowledgements

The research work was supported by National Key Basic Research Program of China （2013CB228203）and the Scientific Research Fund of Sichuan Provincial Education Department (15ZA0058）.

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